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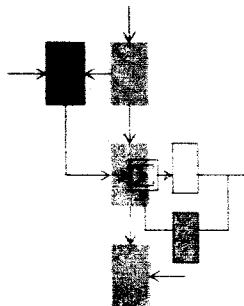
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## PART I COMPUTER-AIDED ELECTRONIC CIRCUIT DESIGN

## PART II CONDUCTION PROCESSES IN THIN FILMS

*Status Report*

*June 1, 1965 - November 30, 1965*

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*Electronic Systems Laboratory*

**MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MASSACHUSETTS 02139**

*Department of Electrical Engineering*

(PART I)

COMPUTER-AIDED ELECTRONIC CIRCUIT DESIGN

and

(PART II)

CONDUCTION PROCESSES IN THIN FILMS

Status Report

June 1, 1965 - November 30, 1965

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## ABSTRACT

26695

Part I relates to a research program in electronic-circuit design through use of on-line time-shared computers. Several developments pertaining to computer programs designated as CIRCAL are described. These developments reflect the current effort to expand and diversify the programs in order to permit handling of a wide variety of network types and configurations. Also presented is a progress report on a separate computer-programming effort pertaining to simulation of nonlinear networks in time-shared computers.

Part II is a status report on research in thin-film conduction processes. As stated in preceding status reports, this work is motivated by a desire to understand better the mechanisms by which conduction takes place in thin semi-insulating films and between sandwich layers of these films. Some items of work which have been in process for almost a year have culminated in either a technical paper or a report. Abstracts of these publications are presented. Continuing research in a thin-film coincident-frequency memory concept is summarized.

J. F. Reintjes  
Professor of Electrical Engineering

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**PART I**

**COMPUTER-AIDED ELECTRONIC-CIRCUIT DESIGN**

Research continues on electrical-network analysis techniques through use of on-line time-shared computers. The family of computer programs designated as CIRCAL (for CIRCUIT anALysis program) has been expanded in several directions as described below.

#### A. CIRCAL: DYNAMIC PROBLEM-SOLUTION METHODS AND PROGRAM EXPANSION

Professor M. L. Dertouzos  
Mr. Charles W. Therrien,  
Research Assistant

CIRCAL permits on-line computer analysis of electrical networks through simulation of the networks.<sup>1</sup> These computational programs have been expanded to include analysis of some nonlinear networks. Various techniques, including matrix inversion and steepest-descent iteration, were experimentally investigated for solving the amnesic network problem, and on the basis of these investigations, a new hybrid method for computing the amnesic network has been developed. (See next section.) The basic data structure which consists of interconnected blocks of storage representing network nodes and branches has not been altered. Even when computation is not performed directly on the data structure, this type of organization is very convenient for generating the required network equations. In addition, by virtue of its one-to-one correspondence with the circuit, this structure is easy to modify when the circuit is modified.

In order to render the solution of the non-amnesic problems more efficient, variable-time-increment integration techniques are being investigated to see how they can be applied to the network problem. These methods involve making a preliminary estimate or "prediction" of the points already computed and then using this predicted value to obtain a more accurate "corrected" value. It can be shown that the corrected value will differ from the real solution by an amount which is of the order of magnitude of the difference between the predicted and corrected values. These methods can be used to advantage as

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<sup>1</sup> Computer-Aided Circuit Design -- Status Report, June, 1965;  
(ESL-SR-245).

follows. An initial time increment which will typically be an order of magnitude larger than the smallest time constant of the network, is selected. The foregoing predictor-corrector method is then applied using this time increment. If the difference between the predicted and corrected values is too large, the time increment is successively decreased until an acceptably small error is obtained. This type of integration can be used to great advantage when the time response of the system is characterized by short periods of fast variation followed by longer periods of relatively slow variation (for example, in computing the response of characteristic of a sharp cut-off filter). Here it is necessary to use a relatively small time increment to observe fast changes, but it would be wasteful of computation time to use this same time increment for the steady part of the response. In such cases, the total time taken to compute overall response may be substantially reduced. Indeed, while prediction and correction doubles the number of computations required per point, the number of points on which computations are performed may be decreased by a factor of ten or more. Currently, computer programs are being written to apply the foregoing techniques to network problems.

Another area of concentration involves expansion of the non-core programs in order to make CIRCAL more flexible to the user. Means have been provided for modifying network topology; through a "remote" command, the user can add or delete branches to the network under simulation. A "heat" command has been added which enables the user to observe the response of the network under simulation, when the components are subjected to changes in temperature.

## B. CIRCAL: STATIC PROBLEM-SOLUTION METHODS

Professor M. L. Dertouzos  
Mr. T. Cruise,  
Graduate Student

This work examines approaches for solution of static problems in CIRCAL. Since analytical evaluation of the efficiency of matrix-inversion techniques versus iteration techniques is at best subject to



"loose" bounds,<sup>2</sup> an experimental approach was taken for their comparison.

For the case of linear circuits, matrix inversion was found to be at least twice as fast as the original iteration scheme used in CIRCAL-1. Moreover, inversion is performed only once and not at each time interval, as in the case of CIRCAL-1 iteration.

On the other hand, iteration-type methods are useful for the solution of nonlinear networks when the nonlinearities are either specified analytically or piecewise-linearly.

Based on these observations, a technique has been developed which combines matrix-inversion and iteration for the solution of arbitrary networks consisting of both linear and nonlinear elements. This approach decomposes the static problem into two coupled subproblems, one linear and the other nonlinear.

#### C. CIRCAL: NONLINEAR-ELEMENT INCORPORATION

Professor M. L. Dertouzos  
Mr. J. Meltzer,  
Graduate Student

The objective of this work is the incorporation of arbitrary nonlinear elements into networks analyzed by CIRCAL.

One method for describing nonlinear elements consists of explicitly and analytically stating their constituent relation (for example, their current-voltage characteristic). Present work involves generation of on-line special-purpose compilers that accept and interpret descriptions of this type and present the results of such an interpretation in a form suitable for CIRCAL. The problem of specifying nonlinear energy-storage elements in terms of state diagrams and interpreting such specifications in a manner useful to CIRCAL, will be investigated next. When these programs are added to CIRCAL-1, the resulting system will be able to accept and "remember" newly defined elements.

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<sup>2</sup> M. L. Dertouzos and C. W. Therrien, "CIRCAL: On-Line Analysis of Electronic Networks." Report ESL-R-248, Electronic Systems Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, October, 1965.

The need for a special-purpose compiler arises because the programming system does not know in advance what type of elements will be described. The compiler must, therefore, generate independent programs that, when called at a later time, can carry out the mathematical relationship that describes any nonlinear element. The family of mathematical expressions for describing nonlinearities that this compiler will accept is fairly general. However, one special case of importance is that of piecewise-linear descriptions. Such descriptions will be always accomplished by defining all breakpoints.

To date, the essential ways in which programs will be generated by the compiler have been determined. Also decided is the manner of cataloging each defined element so that elements can be permanently added to the system, previously defined elements can be called for, and elements can be removed from the system. Sample programs which test almost all these basic ideas have been written and debugged.

Subsequently, these programs will be brought together into a working system that will allow descriptions of straight-line nonlinearities. This system will then be expanded to include analytic descriptions, and state-space methods of describing nonlinear energy-storage elements will be explored.

#### D. CIRCAL: INPUT-OUTPUT CAPABILITIES

Professor M. L. Dertouzos  
Mr. W. Walpert,  
Graduate Student

The objective of this work is the development of input-output structures related to the computer simulation and analysis of electrical networks. Overall goals are to provide an easy-to-use, flexible package which will graphically communicate, through either a cathode-ray tube or a typewriter, information necessary for a particular simulation.

One phase of this problem is the presentation of multivalued functions through the typewriter as the output device. In addition to scaling and dimensioning data, the typewriter must also print out in an efficient manner output data; this will be accomplished through use of the

"tabulate" control. Dimensioning and labeling of the axes is another problem being investigated. An unresolved question is whether the coordinate of each displayed point should be given or whether it is sufficient to label the axes in fixed increments. To date, a program which displays and dimensions the points of a single-valued function, using the tab control, has been written.

#### E. COMPUTER-AIDED DIGITAL-SYSTEM SIMULATION

Professor M. L. Dertouzos  
Mr. Paul Santos,  
Research Assistant

Some time was devoted in re-writing CADD<sup>3</sup> programs for more efficient computation. CADD (Computer-Aided Digital Design) is an on-line system for the synthesis of arbitrary combinatorial digital systems using arbitrary specified sets of building blocks. Revision of these programs became necessary because of redundant man-machine interaction present in CADD-1 version. The rewritten programs of CADD-2 have resulted in a more efficient computational system and a reduction of "design" time by a factor of three or four over CADD-1. Some debugging still remains to be done in CADD-2. A report describing in detail the CADD system is currently being prepared.

In an attempt to generalize analysis and design of digital systems, a new area of computer-aided design is currently being explored-- that of analysis by simulation of both combinatorial and sequential digital systems. Simulation consists of modelling the actual system to be analyzed within computer core memory and reproducing real behavior by stepping through successive states of the model, for each increment of time. Preliminary work has been done on defining the appropriate data structure and on resolving difficulties concerning the accuracy with which realistic digital devices can be simulated.

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<sup>3</sup> M. L. Dertouzos and P. J. Santos, Jr., "CADD: On-Line Synthesis of Logic Circuits," ESL-R-253, Electronic Systems Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, October, 1965.

## F. A GRAPHICAL INPUT-OUTPUT PROGRAM FOR DIGITAL-SYSTEM SIMULATION

Professor M. L. Dertouzos  
Mr. Jeffrey Gertz,  
Graduate Student

This work concerns the input-output interface between designer and analysis programs of the Computer-Aided Digital System Simulation effort. From the graphical, input-output point of view, the interface programs are intended to perform three main functions. First, it will allow the designer to draw a small digital system, in block form, on a cathode-ray tube display by pushing buttons and setting dials (that is, no artistic skill is required). Second, it will permit grouping small systems into larger aggregates and connecting them together to form larger systems. Finally, it will permit the drawing of common system configurations, such as state diagrams for sequential machines and Karnaugh maps for combinational networks either for input or output purposes.

To date, the main objectives have been the implementation of block-diagram drawing. At the present time, existing programs have the following capabilities:

By pushing a button, any one of six gates (AND, OR, NOT, NOR, NAND, EXCLUSIVE-OR) appears at the location of the displayed tracking mark on the cathode-ray tube.

These gates can be oriented in any one of four directions by proper button selection.

From one to nine inputs can be selected for each gate by means of a digital switch.

A combination set-reset and complement flip-flop can be drawn in either of two orientations through use of push buttons.

Any gate can be removed from the system.

Signal-carrying lines can be drawn wherever desired.

Electrical connection between two lines can be indicated by placing a large dot at their intersection.

The entire system can be mechanically translated if desired.

The system picture can be removed from the screen and then displayed at a later time.

Work is now beginning on the problem of transferring the information present in the system block diagram into the appropriate data structure required by the analysis program.

#### G. COMPUTER-AIDED DISTRIBUTED-SYSTEM SIMULATION

Professor M. L. Dertouzos  
Mr. Charles N. Taubman,  
Graduate Student

Many distributive systems in engineering can be expressed and analyzed in terms of iterative electrical-network models. The modeling task consists of two steps: first, the system-defining differential equations are determined, and then an equivalent electrical network characterized by the same equations is generated.

Work in this area involves software development for computer-aided analysis of such systems. The method of attack to be employed is general and can be applied to a wide variety of problems such as electrical transmission lines, blood flow, pneumatic transmission lines, and acoustic channels.

Consider a heat exchanger, as an example. In its simplest form it consists of two concentric pipes. A continual transfer of heat takes place between and along the entire length of these pipes. In addition, heat and mass are continually transported along each pipe. Within the entire system, mass and heat are conserved, and a mathematical analysis can be performed. Execution of such analysis, however, is in general quite complex. Consider also a fractionating column. The function of this system is to operate on a multi-component input chemical mixture in such a way as to yield separate products of the individual components. In the binary case, a two-component mixture of known composition is introduced into the system, and two relatively pure products are obtained. Again, in principle, physical laws will yield an analytic solution but in reality such approaches lead to severe complications because of the existence of nonlinearities and coupling.

The heat exchanger and the fractionating column are distributed systems; that is, an infinite number of lumped-elements representation is required for their exact solution. In reality, an "exact" solution

is not justified, for the values of the parameters themselves are not usually known exactly. A reasonable approach to the foregoing problems is to segment the total system into many identical discrete parts, the number of which is related to the degree of required accuracy. In each segment, corresponding electrical elements can be used, and, if possible, linear approximations can be made to simplify the problem. The next step is simulation by iteration in two dimensions, space and time. That is, at each time interval, a spatial distribution of values is assumed. If certain physical laws are not obeyed by this solution, the assumed values are relaxed accordingly, and a check of the physical laws is again made. This process is repeated until convergence to a solution is achieved within an acceptable error.

A starting point for this research is the iterative procedure used in CIRCAL. It has been shown that under rather broad conditions the iteration method yields relatively quick and accurate answers, applicable to linear as well as nonlinear circuits. This procedure will be extended for the analysis of distributed systems.

#### H. PHASEPLOT: A HYBRID GRAPHICAL-DISPLAY TECHNIQUE

Professor M. L. Dertouzos  
Mr. H. L. Graham,  
Research Assistant

A hardware-software technique for graphical display of computer data is being investigated. This technique is motivated by the mechanical plotting principle described in Status Report ESL-SR-245 and has the advantage of being able to display continuous curves with a minimum number of computer commands.

The output device is a storage-type cathode-ray tube. Inputs  $x$  and  $y$  to the tube are driven by linear networks  $T_x$  and  $T_y$ , each having unity steady-state gain. A set of computer words specifies, at any given time,  $x$  and  $y$  beam coordinates and parameters of the linear networks. Values of  $x$  and  $y$  coordinates determine initial and terminating points, while the curve connecting such points depends upon the computer-controlled parameters of  $T_x$  and  $T_y$ .

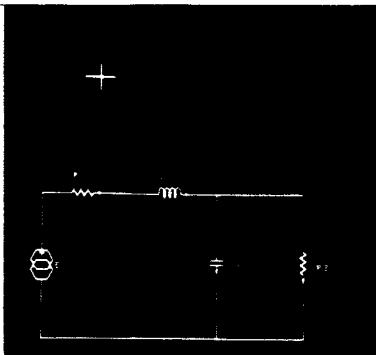


Fig. 1. Esaki diode circuit as drawn on the ESL display unit oscilloscope.

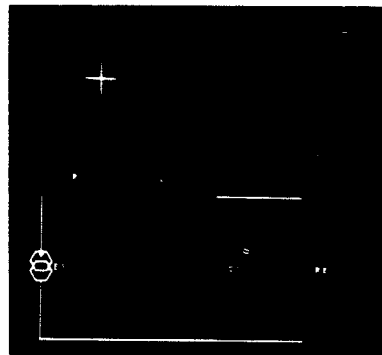


Fig. 2. Checking the topology of the voltage sources. No loops of voltage sources.

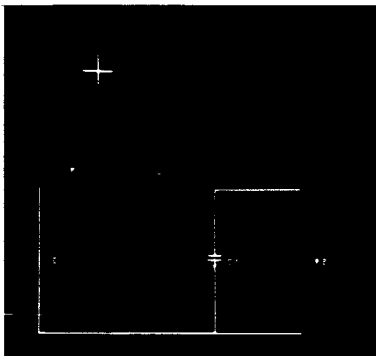


Fig. 3. Checking the topology of the capacitors; C1 can be charge controlled.

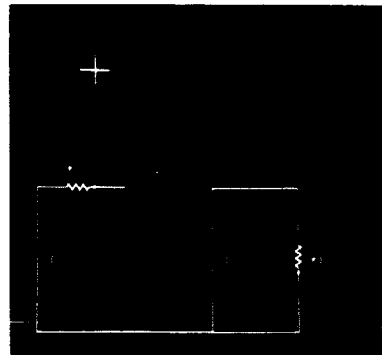


Fig. 4. Checking the topology of the resistors; R1 can be current-controlled, R2 can be voltage controlled.

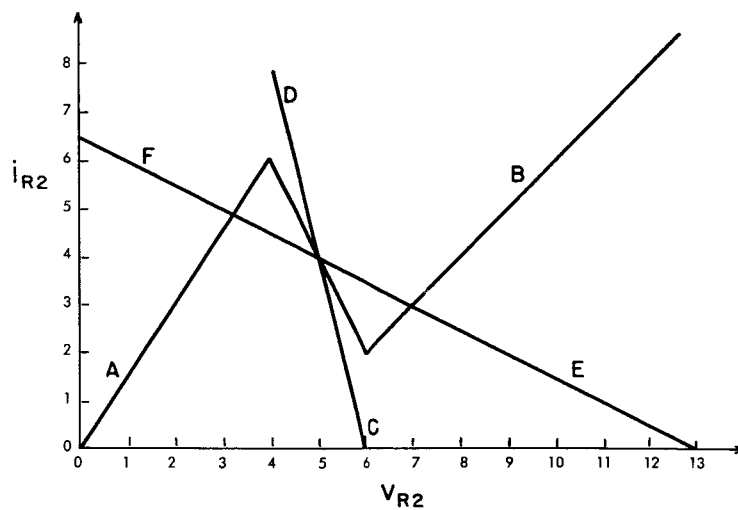


Fig. 5. The characteristics of R2 and the load line.

For example, if  $T_x$  and  $T_y$  are tuned (that is, if they are identical), then initial and final points will be connected by a straight line. De-tuning the two networks in different ways and by different amounts results in a family of different curves connecting the two points.

Preliminary design of the system has been completed. Networks  $T_x$  and  $T_y$  will each consist of two RC subnetworks. One of these subnetworks will have a fixed time constant while the time constant of the other will be computer controlled. A second parameter, also controlled by the computer, specifies the fraction of the output of each RC subnetwork to be summed at the output.

Since four independent quantities are computer controlled, the system has four degrees of freedom. Two of these are used to specify the coordinates of the connected points, and the remaining two specify the particular curve connecting the points. Thus, initial and final slope can be matched leaving one degree of freedom for curvature. Alternatively, initial and final slope can be ignored resulting in a larger selection of curves to join the points.

A breadboard model of the system is presently being constructed and tested. Evaluation and finalized system design remain to be completed.

## I. SIMULATION OF NONLINEAR NETWORKS

Dr. Jacob Katzenelson,  
Staff Member  
Mr. D.S. Evans,  
Research Assistant

The object of this project is to obtain a digital-computer program for simulation of electronic circuits containing a wide class of non-linear elements. The simulation system features on-line use of a time-shared computer and an oscilloscope display console which is used as a graphical input-output device. The theoretical background of this work was described in the preceding status report ESL-SR-245. The same report discusses the structure of the simulation system and the main considerations in its design. This report describes the current capability of the system, illustrates its performance by an



example, and discusses short and long-term extensions of the work. The simulation system currently consists of two parts: the graphical-communication part and the analytic part.

### 1. Graphical Communication Part

The main purpose of the graphical communication part is to enable the user to specify his network by drawing it on the cathode-ray-tube display unit. An example of such a drawing is given in Fig. 1. In addition to the circuit diagram, the user assigns names and values to the elements. Linear elements are specified by a single number; for example, a linear resistor is designated by its value in ohms. The characteristics of piecewise-linear elements are specified to the computer either by drawing the characteristics on the oscilloscope or by typing the values of the breakpoints on the teletype. Nonlinear elements can be represented in the computer by a subroutine which specifies, in the case of a voltage-control resistor, the current as function of the voltage. The user specifies the name of the subroutine and the system asks the user for loading instructions in case the subroutine is not in core memory.

The network elements should satisfy certain topological relations in order that the network will have a unique solution for any initial conditions (see ESL-SR-245 for explanation). This relation can be checked with the help of the display unit, as illustrated by Figs 2 to 4. In Fig. 2 all elements are open except voltage sources. The circuit, as the figure illustrates, does not contain any loops which consists of voltage sources only. Figure 3 checks the capacitor. Capacitor C1 is an open branch and therefore can be nonmonotonic and charge-controlled.

Currently, the analytic part gets its input by reading a file from the magnetic-disk-storage unit, rather than through the graphical-communication part. Although the graphical-communication part is operative, it is not yet connected to the analytic part. The program for the interface between the two parts is now being debugged.

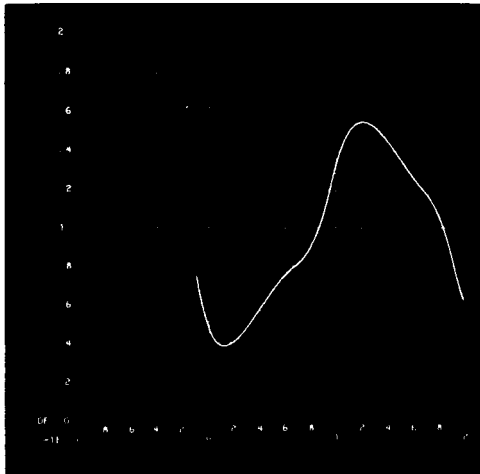


Fig. 6. Charge on C1 as function of time.

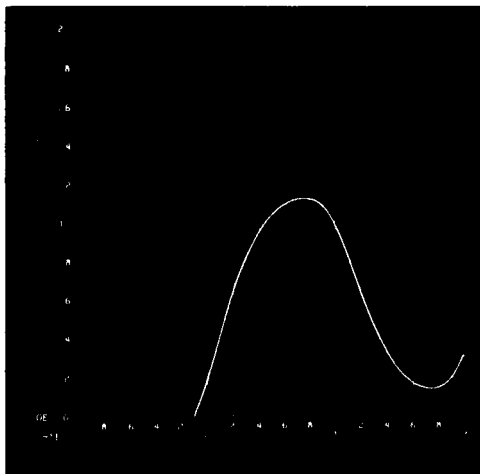


Fig. 7. Flux on L1 as function of time.

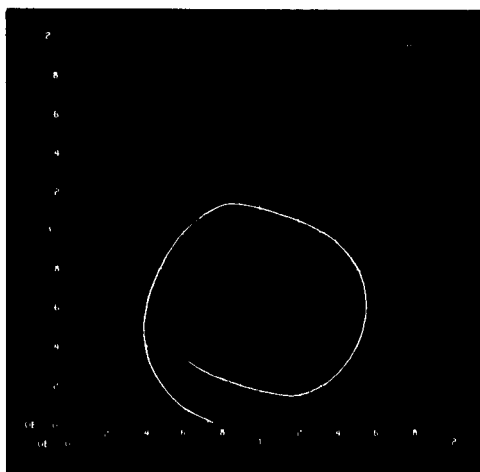


Fig. 8. Flux as function of time, the oscillation approaches a limit cycle.

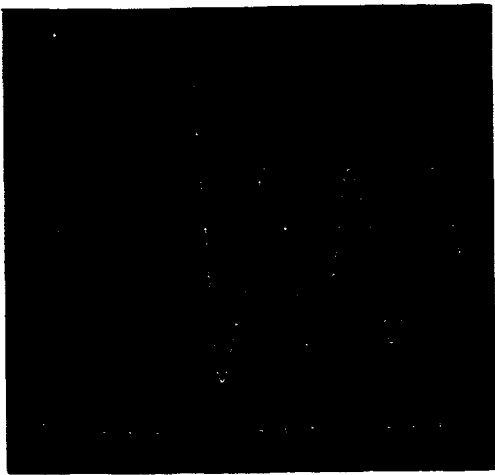


Fig. 9. C1 and L1 changed to increase the frequency of oscillation. Charge as function of time.

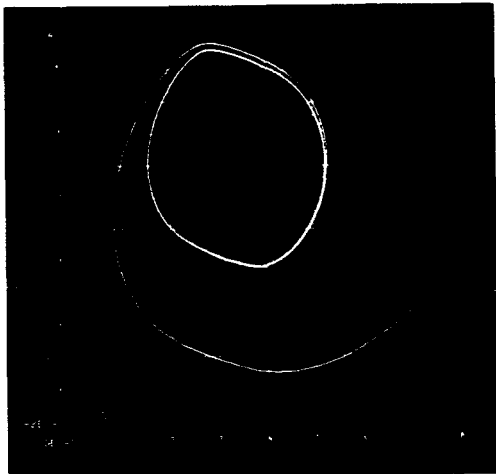


Fig. 10. C1 and L1 changed to increase the frequency of oscillation. Flux as function of charge.

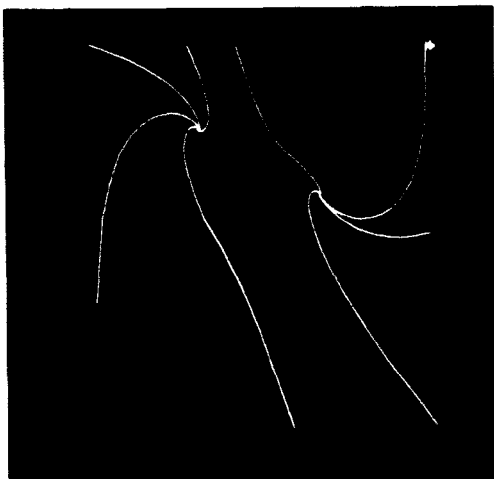


Fig. 11. R1 changed to form a bistable circuit. Trajectories to stable points from several initial conditions. (Flux on L1 as function of charge on C1.)

## 2. The Analytic Part

The analytic part of the simulation system is the part which actually calculates the circuit response. The analytic part can now solve networks which consist of dependent and independent sources and RLC elements. The RLC elements can be linear or nonlinear. The characteristics of the nonlinear elements can be either monotonic or nonmonotonic and, as mentioned above, are represented in the computer by either a table (for piecewise-linear elements) or by a subroutine.

Once the response of a circuit has been calculated the user can ask the system to display any waveform in the network, observe the results, change the values of the elements and ask for recalculation of the response and a re-display of the waveforms. At present, topological changes in the network require the editing of the input file. Once the graphical-communication part is connected with the analytical part, these changes will become as straightforward as value changes are now.

The performance of the analytic part is illustrated by Figs. 5 through 11. The circuit undergoing analysis is the circuit of Fig. 1.  $E_1$  is a constant-voltage source;  $R_1$ ,  $C_1$ , and  $L_1$  are linear and  $R_2$  is an Esaki diode which is represented by a nonlinear voltage-controlled resistor whose characteristics are given in Fig. 5 (broken lines AB). Now, if the value of the resistor  $R_1$  and the source  $E_1$  are chosen such that the load line CD intersects AB in the negative part of the characteristic, the circuit behaves as an oscillator.

Figures 6 and 7 show the charge on  $C_1$  and flux on  $L_1$  as functions of time. Figure 8 describes the flux as a function of the charge and illustrates the way in which the oscillation approaches a limit cycle. Figures 9 and 10 show the relations between the same variables as in Figs 6 and 8 after the frequency of oscillation has been increased by decreasing the capacitance and the inductance (initial conditions were not changed).

By changing the value of  $R_1$  and  $E_1$  (load line EF, Fig. 5) the circuit becomes a bistable device. Figure 11 describes the trajectories in which the stable points are reached from several initial conditions.

### 3. Future Plans

We are now engaged in connecting together the two parts of the simulation system. This mainly involves the debugging of the interface between the graphical communication part and the analytic part. The next step is to extend the system capability to handle additional types of dependent sources and to incorporate the CADET system (Computer-Aided Design experimental translator) as an input device which will enable flexible communication between the user and the program.

## PUBLICATIONS OF THE PROJECT

### CURRENT PUBLICATIONS

#### REPORTS

Computer-Aided Electronic Circuit Design, Status Report ESL-SR-245, June 1965.

M. L. Dertouzos and C. W. Therrian, "CIRCAL: On-Line Analysis of Electronic Networks", Report ESL-R-248, December, 1965.

#### THESES

Fluhr, Z. C., "Single-Threshold Element Realizability by Minimization", S. M. Thesis, Massachusetts Institute of Technology, Department of Electrical Engineering, August, 1965.

Olshansky, K. J., "A Low-Cost Teletype-Operated Graphical Display," S. M. Thesis, Massachusetts Institute of Technology, Department of Electrical Engineering, August, 1965.

### PAST PUBLICATIONS

#### REPORTS

Computer-Aided Electronic Circuit Design, Status Report ESL-SR-225, December, 1964.

#### THESES

Dvorak, A. A., "An Input-Output Program for Electronic Circuits Using a CRT", Bachelor of Science thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1965.

Santos, P., "CADD, A Computer-Aided Digital Design Program", Master of Science thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, June, 1965.

Therrian, C. W., "Digital-Computer Simulation for Electrical Networks", Master of Science thesis, Massachusetts Institute of Technology, June, 1965.

PART II  
CONDUCTION PROCESSES IN THIN FILMS

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## A. CONDUCTION PROCESSES IN THIN FILMS OF CADMIUM SULFIDE

Professor J. G. Gottling  
Mr. W. Stewart Nicol,  
Staff Member

A report on the conduction processes in CdS thin films is in preparation. This report contains results obtained on measurements of donor and trapping-energy levels by means of thermally stimulated currents, metal-CdS film barrier studies, the fabrication of several categories of CdS diode as determined by their current-voltage characteristics, and negative-resistance in CdS films. Also to be included in the report is a discussion of the relative importance of impurities, trapping levels, and barriers controlling the conduction mechanism. This information is directly related to the study of a thin-film active device, and will guide the research on this device.

## B. DOUBLE-LAYER INTERFERENCE IN AIR-CdS FILMS

Professor J. G. Gottling  
Mr. W. Stewart Nicol,  
Staff Member

The measurement of thin-film thickness by the method which uses a reflecting contour film and obtains the Fizeau fringe shift at the thin-film edge is well known.<sup>1</sup> Where it is inconvenient to apply a contour film, a transmission method can be used.<sup>2</sup> It has been found possible, however, to use a reflection method without the requirement of a contour film. This method and an analysis are given in a paper being submitted for publication. The abstract of this paper follows:

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<sup>1</sup>S. Tolansky, "Multiple Beam Interometry of Surfaces and Films", Oxford, Clarendon Press, (1948).

<sup>2</sup>A.C.S. Van Heel, A. Walther, Opt. Acta 5, 47 (1958).

"Fringe-step displacements have been observed in CdS films deposited over reflecting metallic films. The fringe-step structure is accounted for by a Fresnel reflection-coefficient analysis of double-layer multiple reflection within the dielectric and an air film, formed between the cadmium sulfide film and a half-silvered mirror. The analysis provides a basis for film-thickness measurement of nonabsorbing dielectric films when it is not convenient to apply an overlay film to measure the film thickness by Fizeau fringe shift."

#### C. STUDY OF CdS THIN-FILM VACUUM ANALOG TRIODES

Mr. W. Stewart Nicol,  
Staff Member  
Mr. Anthony A. Aponick,  
Staff Member  
Mr. Stephen Teicher,  
Undergraduate Student

The investigation of the possibility of fabricating thin-film vacuum analog devices using only vacuum deposition techniques was continued. It was found that the problem of effectively insulating the grid from the CdS excluded the use of either gold or silver as grid material. This was solved by the use of aluminum which can be readily oxidized to provide insulation. Several devices were fabricated which operated in an "enhancement" mode, in which there is a back-biased blocking contact region at the emitter-CdS film junction and the grid potential essentially modulates or enhances the current flow over the back-biased contact. These devices operated with the correct sense of grid-potential modulation of the collector current but had less than unity gain. No modulation of collector current was observed in a "normal" mode of operation with the emitter contact being an electron injecting contact. This work is reported in Technical Memorandum ESL-TM-247, "A Study of CdS Thin-Film Vacuum-Analog Triodes", by A. Aponick. The abstract of this Memorandum is reproduced as follows:

"Previous investigations of thin-film gold structures on CdS have shown that gridlike structures with 40-50 percent open area, and sheet resistance 12-50  $\Omega/\text{sq.}$  can easily be fabricated.

An investigation is made of the possibility of incorporating these structures into active vacuum-analog devices. Solutions to two of the basic problems in achieving this goal are presented and discussed.

The first of these problems, that of insulating the grid structure from the CdS in which it is imbedded is solved by using aluminum grid material and insulating it with a combination of blocking contact and oxide insulating layer.

The second of these problems, that of achieving a non-linear conduction law in essentially ohmic polycrystalline CdS, is solved by employing an emitter which makes blocking contact to the CdS. The grid is then used to "pull" electrons over the barrier thus induced in front of the emitter.

The characteristics of such a device which operate in the expected way, but which produce less than unit gain, are presented."

Mr. Aponick has suggested that for readily oxidizable metals, such as aluminum, grid fabrication should be carried out in an inert gas atmosphere. Further research has demonstrated that a grid having 1-micron apertures can be formed from a 100- $\text{\AA}$  layer of aluminum by heating to 425  $^{\circ}\text{C}$  for 10 minutes. The surface resistivity increases by a factor of 2.5 during grid formation and does not change during cooling. Before evaporation of the aluminum, the vacuum system is first filled with argon at 50 microns, Hg, and is then pumped down to  $10^{-5}$  mm, Hg. Provided grid formation is carried out immediately after evaporation, the presence of argon is not required during grid formation.

Further research will be necessary to find the variation of device gain with aperture size for an aluminum grid, to obtain the best position for the grid in the enhancement mode operation, and to investigate if "normal" triode operation can be obtained with space-charge-limited currents at an ohmic emitter contact. The use of recrystallized CdS films is being considered for this purpose.

D. SPACE-CHARGE DISTRIBUTION IN CdS THIN-FILM DIODES

Professor J. G. Gottling  
Mr. Mark S. Cooper,  
Graduate Student

Space-charge distribution in the region of a metal-CdS thin-film blocking contact has been investigated by the method of differential capacitance measurements. This study was made through a thesis project, the abstract of which is given below:

"Cadmium sulfide thin-film diodes are prepared by evaporation at pressures of  $5 \times 10^{-5}$  to  $10 \times 10^{-5}$  torr. The surface of the blocking contact of CdS is treated by glow discharge in argon. Gold is used for the blocking contact and indium for the ohmic contact.

Capacitance-voltage tests and capacitance-temperature tests are performed. The capacitance-temperature data reveal a straight-line relation near room temperature, while a log-log plot reveals a variation of  $C$  with  $T$  to the 2.5 power. The inverse square of capacitance vs. bias voltage curves differ from the theoretical (Schottky) curve by a negative second derivative near the zero-bias point and a positive second derivative at positive bias. Certain diodes show no second-derivative region.

Several models of the space-charge distribution are postulated to explain this behavior. The negative second-derivative region in the inverse-square-of-capacitance curves may be due to influx of gold acceptors into the CdS and to the increasing ionization of donors as the potential for electrons rises in the depletion layer. The positive second-derivative region may be due to the decrease of the Fermi level in the contact region with conduction, by the drive of ionized donors in the space charge layer, or by the presence of a small insulating region between the gold and the CdS.

The capacitance-temperature data can be explained by taking a straight-line approximation to the Fermi-distribution of ionized donors. This results in an exponential variation for the reverse region charge density, voltage, and energy-level curves. This model also predicts a capacitance-temperature curve whose slope increases at higher temperatures."

## E. A COINCIDENT-FREQUENCY MEMORY USING THIN MAGNETIC FILMS

Professor A. K. Susskind  
Dr. H. Ishida and  
Mr. W. Stewart Nicol,  
Staff Members

Coincident-current memories using magnetic-core memory elements are widely used. When there are  $N^2$  words in a coincident-current memory, all the words are arranged in a two-dimensional fashion in the form of an  $N \times N$  matrix. The selection of a particular word is accomplished by choosing the word at the intersection of one of  $N$  rows of words and one of  $N$  columns of words. Thus the number of necessary selection lines is  $2N$ . By contrast, all  $N^2$  words are arranged in a one-dimensional column in a word-organized memory and the number of necessary selection lines is  $N^2$  in such a memory. It is obvious that a great saving of selection circuitry is achieved in the coincident-current memory, thus making the whole organization simpler.

Since magnetic thin films were first investigated by M. S. Blois,<sup>3</sup> they have been extensively studied in a number of memory systems. Nearly all are word-organized; a coincident-current thin-film memory has not yet been successfully constructed. A special form of such a memory is under investigation.

One can classify memories depending upon whether the readout of stored information is done destructively (DRO) or nondestructively (NDRO). Generally an NDRO memory has faster operating speed because there is no need to rewrite, and reliability tends to be higher.

The memory concept under investigation uses a radio-frequency readout scheme, having a keyed current of frequency  $f_1$  driving the selected column and a keyed current of frequency  $f_2$  driving the selected row. Only the film elements at the intersection of the selected column drive line and the selected row drive line are energized by fields of both frequencies  $f_1$  and  $f_2$ . The film elements act as

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<sup>3</sup> M. S. Blois, Jr., J. App. Phys. 26, 975 (1955).

nonlinear mixing elements to produce a subfrequency output  $f_1 + f_2$ . The output phase is 0 or  $\pi$ , depending on the direction of magnetization of the selected film element. Noise elimination is expected to be easier because the output is picked up through filtering.

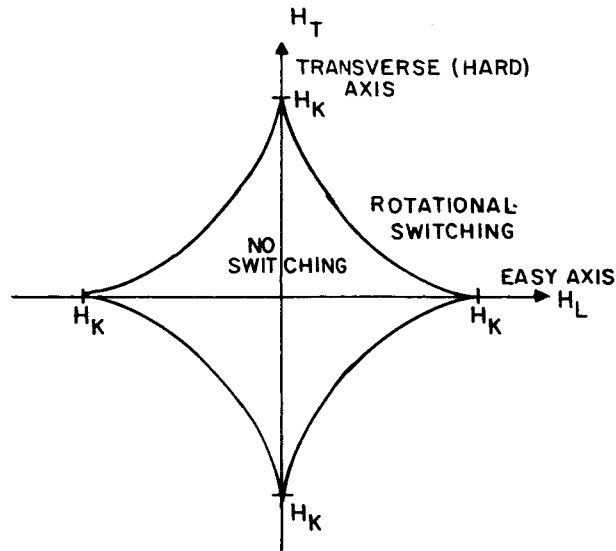
Compared with cores, thin magnetic films are considered to be more ideally suited for the r-f NDRO scheme because of their strong second-order nonlinearity. It has been confirmed by our experiment that the scheme is successful as a means of nondestructive readout.

The use of thin films in a coincident-current memory, however, creates several problems in the write (switching) mode. Figure 1(a) shows the critical switching curve according to the Stoner-Wohlfarth theory<sup>4</sup> in which the film magnetization rotation takes place as a single domain. For practical films, however, the critical switching curve takes the form shown in Fig. 1(b). For sufficiently large combinations of applied transverse field,  $H_T$ , and longitudinal field,  $H_L$ , switching can take place by coherent rotation, where edge domains, imperfections, etc., do not have an important role in the reversal process.<sup>5</sup> There are, however, several regions of importance to the operation of a coincident-current memory. The region of domain-wall motion is one in which magnetization reversal takes place by the movement of walls across the film, travelling in the direction of the longitudinal field. These walls start from nuclei of reversed magnetization at the film edges, which are created by the demagnetizing field. The region of noncoherent rotation is where the magnetization rotates by a different amount in different parts of a film, resulting in partial switching. In this case domain walls are nucleated either by physical imperfections such as crystalline vacancies, dislocations, inclusions, etc., or by inhomogeneous demagnetizing fields, or dispersion of the

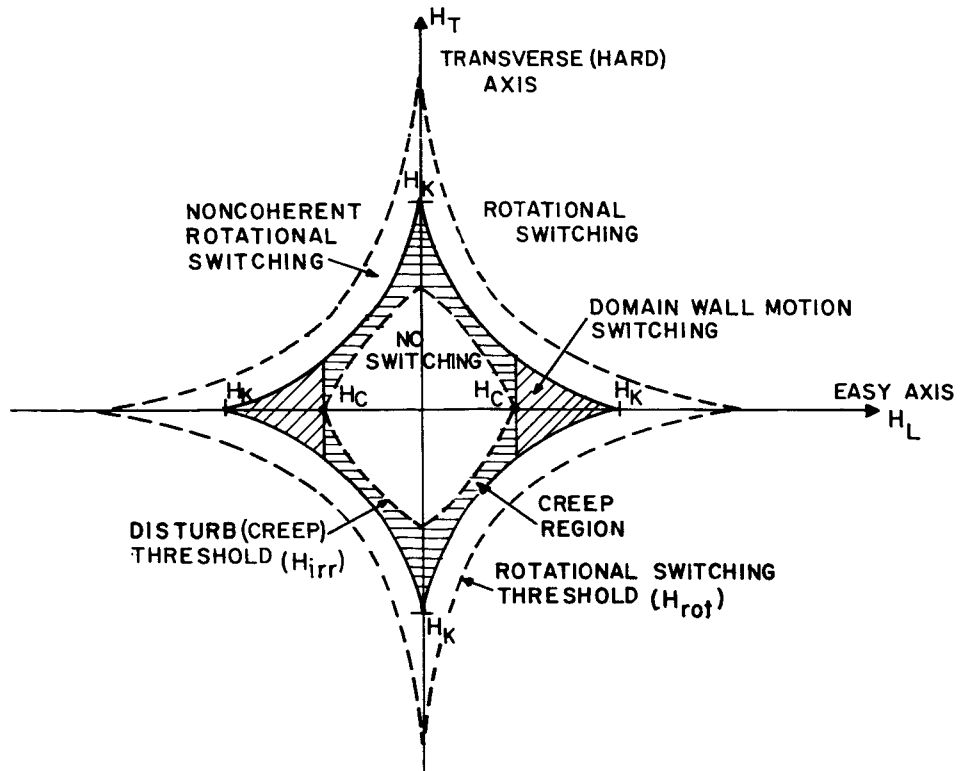
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<sup>4</sup> E. C. Stoner, E. P. Wohlfarth, Phil. Trans. Roy. Soc. London, 240A, 599 (1948).

<sup>5</sup> A. V. Pohm, E. N. Mitchell, IRE Trans. EC-9, 308 (1960).



(a) Stoner-Wohlfarth Model



(b) Practical Model

Fig. 1. Critical switching curve for a uniaxial film.



axis of uniaxial anisotropy (easy axis) in magnitude and direction.<sup>6</sup>

The region of creep is where domain-wall motion occurs when a number of magnetic field pulses are applied in a direction other than along the easy axis, even though their magnitude is less than the d-c threshold in the Stoner-Wohlfarth curve. Several theories of creep have been given in the literature.<sup>7, 8</sup>

The major limitations which the presence of these various regions imposes on memory applications of thin magnetic films lie in the control of drive-current amplitudes and duration, in the proportion of the magnetization within a cell which is switched (this is related to the switching time), and in the retention of stored information.

During the write mode the aim is to have coherent rotational switching of the magnetization. For coherent rotational switching, the switching time is extremely rapid, being less than  $0.1 \mu \text{ sec.}$ , possible values being of the order of several nanoseconds. The drive currents may, however, be required to be fairly large, with peak values of the order of one or two amperes. The same considerations apply to the read mode in a memory using a DRO scheme, in which switching of the magnetization takes place.

Drive currents which result in applied fields in the noncoherent region give rise to slower switching times ( $0.1 \mu \text{ sec.}$  to  $1 \mu \text{ sec.}$ ) and conditions of partial write due to the nucleation of fine domain structures. For fields applied in the creep region there is a subsequent loss of the stored information.

The domain-wall switching process is inherently slow, having associated switching times greater than  $1 \mu \text{ sec.}$ , and results in partial information storage for pulses of duration shorter than the switching time.

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<sup>6</sup> D. O. Smith, K. J. Harte, J. App. Phys. 33, 1399 (1962)

<sup>7</sup> S. Middlehoek, "Domain Walls in Thin Ni-Fe Films," IBM Res. Rep. RC846 (Dec. 1962).

<sup>8</sup> T. H. Beeforth, P. J. Hulyer, Nature 199, 793 (1963).

1. Non-Destructive Read-Out Mode

The layout of a nine-word coincident-frequency memory with three bits in each word is shown in Fig. 2. The memory so far tested has consisted of three 3-bit words arranged in a similar way. The r-f read-out drive frequencies currently used are 20 Mc and 40 Mc, with the read-out signal amplified through a band-pass sense amplifier tuned to 60 Mc. Experimentally, no difficulties have been encountered in the NDRO mode.

In order to gain quantitative insights into the NDRO mode, it was found necessary to resort to numerical techniques, because the pertinent equations are highly nonlinear. An IBM 7094 computer program written by Dr. H. Ishida determined the effects of easy-axis skew angle,  $\alpha$ , drive amplitudes  $H_f$  and  $H_{2f}$ , d-c bias fields  $H_{TO}$  and  $H_{LO}$ , and phase difference,  $\beta$ , between the two drive fields. The results are summarized as follows:

a. Drive-Amplitude Dependence. Figure 3 shows the drive-amplitude dependence of the output signal with  $\alpha = \beta = H_{TO} = 0$ .  $H_{LO} = 0.01$ . When one drive amplitude is fixed, a maximum output results for  $H_f + H_{2f}$  slightly larger than 1. When both  $H_f$  and  $H_{2f}$  are increased, the output continues to increase and reaches a maximum at about  $H_f + H_{2f} = 2.3$ , where the negative peak of the combined drive reaches -1.

b. Effect of a D-C Longitudinal Field,  $H_{LO}$ . Figure 4 shows the d-c longitudinal-field dependence of the output when there is no skew and also when there is a  $10^\circ$  skew angle ( $\alpha = 10^\circ$ ,  $H_f = H_{2f} = 0.25$ ,  $\beta = H_{TO} = 0$ ).

c. Effect of Skew Angle,  $\alpha$ . When there is skew, the binary outputs are not symmetric in amplitude as seen in Fig. 4. Asymmetry also arises in switching thresholds.

d. Effect of a D-C Transverse Field,  $H_{TO}$ . This effect is shown in Fig. 5. It is to be noted that the r-f field is not symmetric in amplitude in the positive and negative directions. Since  $H_T = H_f \cos \omega t + H_{2f} \cos 2 \omega t$ , there are three kinds of peaks in  $H_T$

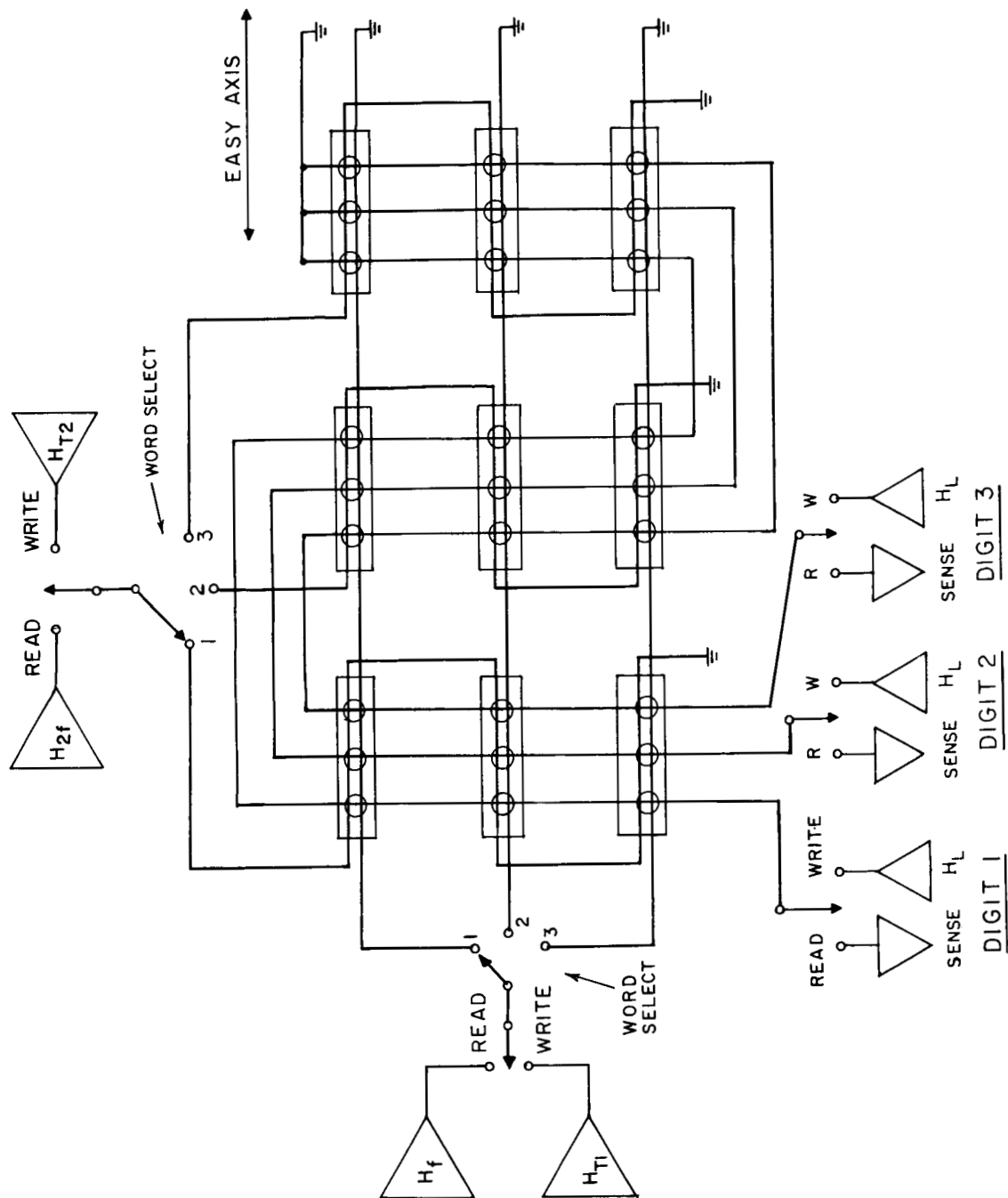


Fig. 2. A nine-word coincident-frequency memory having 3 bits per word.

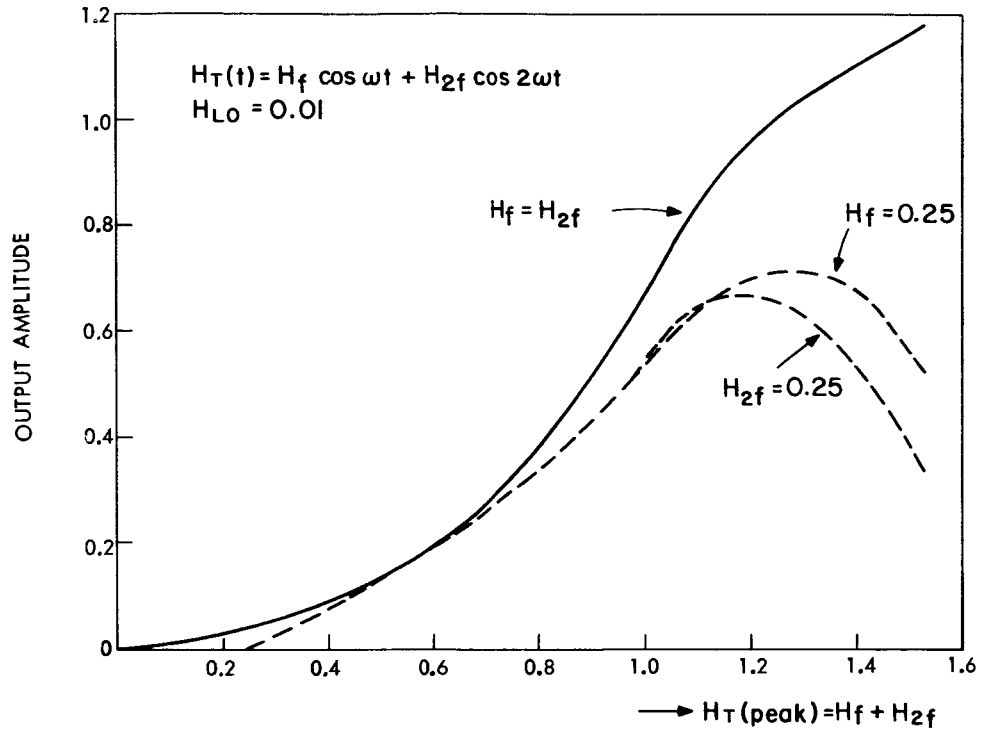


Fig. 3. Variation of output amplitude with transverse drive field.

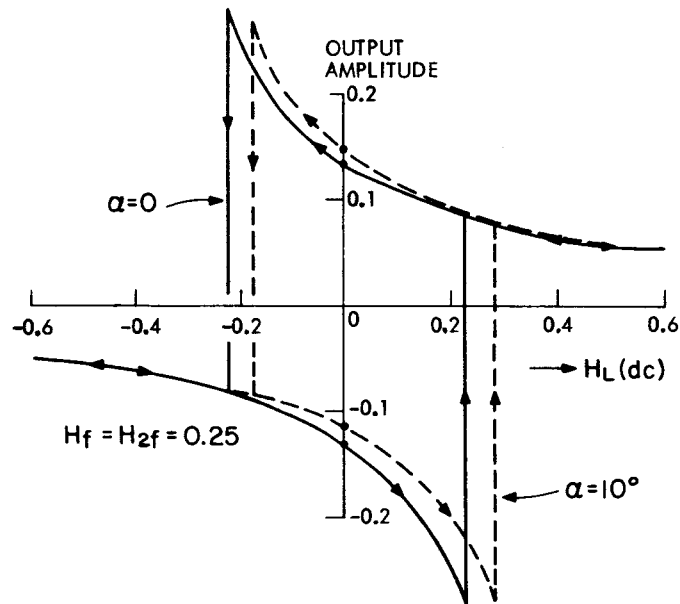


Fig. 4. Variation of output amplitude with d-c bias field along the easy axis.

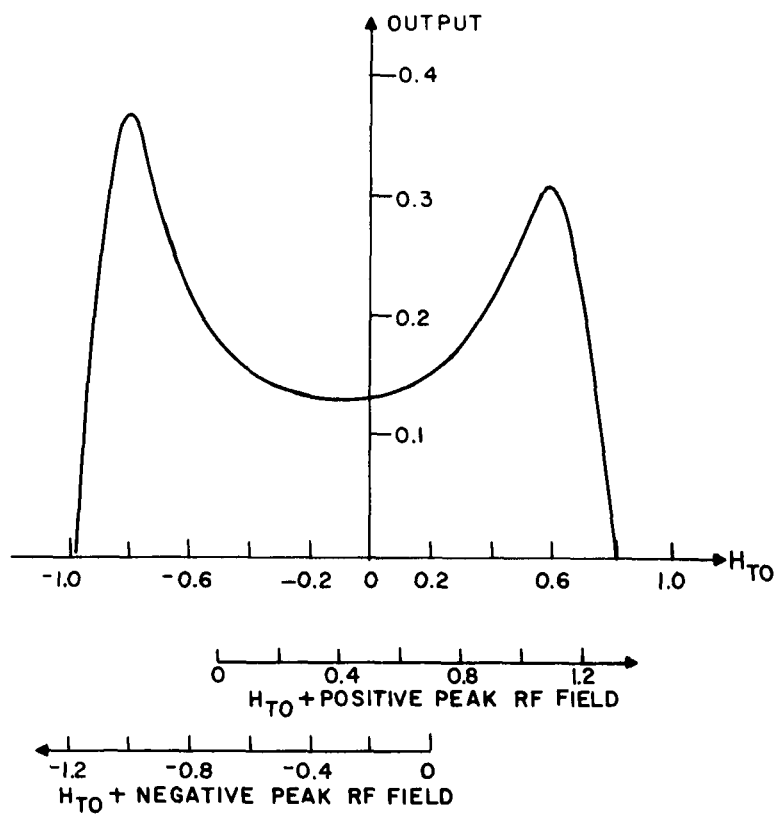


Fig. 5. Effect of a transverse d-c field.

determined by

$$\frac{dH_T}{dt} = -\omega \sin \omega t (H_f + 4H_{2f} \cos \omega t) = 0$$

That is, a positive peak =  $H_f + H_{2f}$  when  $\omega t = 0$

a middle peak =  $-H_f + H_{2f}$  when  $\omega t = \pi$

a negative peak =  $\frac{-H_f^2}{8H_{2f}} - H_{2f}$  when  $\cos \omega t = \frac{-H_f}{4H_{2f}}$ .

The presence of a d-c field,  $H_{TO}$ , tends to increase the output. The maxima occur at approximately  $H_f + H_{2f} + H_{TO} = 1.1$  and at  $\frac{H_f^2}{8H_{2f}} - H_{2f} + H_{TO} = -1.1$ .

e. Effect of a Phase Difference,  $\beta$ . Under a typical condition ( $H_f = H_{2f} = 0.25$ ,  $\alpha = H_{TO} = H_{LO} = 0$ ), the presence of  $\beta$  merely introduces a phase shift in the output and there is no change in the total amplitude  $A(3\omega)$ .

The range of NDRO drive currents used experimentally is from 100 to 400 ma, peak-to-peak, with sense-amplifier outputs of several volts, peak-to-peak, for films between 200 Å and 1000 Å thick.

## 2. Coincident-Current Writing

### a. Nature of the Problem Due to the Requirement of Coincidence.

The main problem in the coincident-current write (switching) mode is that the rotational switching threshold,  $H_{rot}$ , is considerably higher than the threshold of the idealized Stoner-Wohlfarth theory, whereas the disturb threshold,  $H_{irr}$ , is considerably lower than the idealized threshold. While there is no upper bound on the transverse field in a word-organized memory, the transverse field in a coincident-current memory is bounded. The bounding condition is that stored information in half-selected cells must not be destroyed by the drive fields. These fields are either  $H_L$  or the combination of  $\frac{1}{2}H_T$  and  $H_L$ , where a transverse field,  $H_T$ , plus a longitudinal (easy-axis) field,  $H_L$ , are the switching fields in fully-selected cells. If  $H_T$  is too large, the field at half its strength together with  $H_L$  will very likely disturb half-selected

cells due to creep, especially when the fields are applied many times. On the other hand, if the transverse field is kept low to avoid disturbing half-selected cells, only partial switching will occur in fully-selected cells as the result of noncoherent rotation. The question, then, is whether it is possible to find a field combination  $H_T$  and  $H_L$  which can create rotational switching in selected cells while not disturbing half-selected cells.

A possible write scheme to combat the difficulty of creeping may be to use r-f fields both as the transverse and longitudinal fields:

$$H_{T1} = \frac{1}{2} H_T \cos \omega t, H_{T2} = \frac{1}{2} H_T \cos 2 \omega t, H_L = \pm H_L \cos \omega t.$$

In half-selected cells receiving  $H_{T1}$  and  $H_L$  or  $H_{T2}$  and  $H_L$ , it is possible that the magnetization would undergo a symmetric displacement during each half-cycle, and so inhibit creeping. This has yet to be tried with sufficiently large drive currents.

### 3. Experimental Results of Pulse Writing

Most of the tests have so far been conducted on films supplied by M.I.T. Lincoln Laboratory. These were of thickness between 180 Å and 1000 Å with  $H_k$  between 2.4 oe and 3.4 oe, and were vacuum evaporated onto glass substrates. They have been used both in continuous sheet and in 20-mil or 40-mil wide photo-etched strip form, with the length of the strip along the easy axis.

The experimental configuration consists of a copper ground plane, 40-mil thick glass substrate, magnetic film, 0.5-mil mylar sheet, longitudinal (sense) line (1-mil thick, 40-mil wide), 6-mil thick epoxy circuit board, first word (transverse) line (1-mil thick, 40-mil wide), 0.5-mil mylar sheet, second word (transverse) line (1-mil thick, 40-mil wide).

Pulse writing is done by the coincidence of a single set of a longitudinal pulse (of polarity chosen to store either 0 or 1),  $H_L$  ( $\pm 150$  ma peak, duration variable), and a transverse pulse,  $H_T$  (1.2-ampere peak, 100-ns duration), when the cell is fully selected. When the cell is half-selected, disturbance is created by a train of  $H_T/2$  and  $H_L$  pulses to see if the previously written information is destroyed.

The following qualitative comparisons have been made between continuous sheet and etched films. For continuous sheet films ( $600 \text{ \AA}^{\circ}$  -  $1000 \text{ \AA}^{\circ}$ ):

- a. D-c switching caused by a strong magnet appears to take place very rapidly.
- b. No intermediate state is induced by a magnet.
- c. The amount of switching (by pulses) depends on the number of applied pulses, indicating creep.
- d. There is spontaneous switching from a reversed state back to the previous or some intermediate state, a few seconds after the write pulses are removed.
- e. The amount of switching and the stability of a reversed state are extremely susceptible to a d-c bias field,  $H_{LO}^{\circ}$  (longitudinal field).

The same characteristics have been observed in some  $250 \text{ \AA}^{\circ}$  to  $400 \text{ \AA}^{\circ}$  films.

For 40-mil etched films:

- a. D-c switching, as observed on an oscilloscope, appears to take place very slowly.
- b. Many intermediate states can be induced by a permanent magnet close to the film.
- c. No spontaneous switching is observed.
- d. Switching is not so sensitive to  $H_{LO}^{\circ}$ .
- e. Switching becomes more difficult, indicating an increase in the effective  $H_K$ .
- f. The amount of switching by a large pulse,  $H_T$ , in coincidence with  $H_L$  is approximately the same as that resulting from many small pulses,  $H_T/2$ , in coincidence with the same  $H_L$  pulses.

The best results so far have been obtained with a  $250\text{-}\text{\AA}^{\circ}$ , 20-mil wide strip film. The amount of switching is about 50 percent of total possible output with  $H_T = 1$  amp and  $H_L = \pm 150$  ma, while disturbance is negligible with  $H_T = 500$  ma and  $H_L = \pm 150$  ma.

From these results it became apparent that the simple model of film switching was quite inadequate. It was decided, therefore, to proceed in several complementary ways:



- a. An investigation of the factors influencing the switching of films assuming that they behave according to the idealized Stoner-Wohlfarth theory;
- b. The fabrication of magnetic films in our laboratory which would have properties better suited for use as coincident-frequency memory elements;
- c. The visual observation of the domain structure of films into which information has been written in the memory.

#### 4. Factors Influencing Switching of Ideal Films

In addition to the fact that a magnetic thin film never switches exactly like the ideal single-domain model because of creep, incoherent rotation, and wall motion, there are also a variety of reasons why the film does not switch at the thresholds predicted by theory even if the film itself were the ideal one of the Stoner-Wohlfarth theory. The main factors are: nonuniformity of drive fields applied through strip lines; demagnetizing field; film shape and edge effect; eddy currents in the drive lines; and capacitive coupling between the lines. Some of these factors were studied and the results are summarized below.

a. Nonuniformity of the Applied Fields. Magnetic fields applied to thin films are usually expressed in terms of a scalar function of the currents in the drive conductors. This is appropriate for the case of uniform fields such as those produced by Helmholtz coils, very wide strip lines, or the circumferential field in a cylindrical film produced by the current in its round wire substrate.

For fields produced by narrow strip lines, however, the use of a scalar function is often misleading, because the fields are not uniform over a memory cell. Two entirely different expressions for the strip-line fields can be obtained, depending upon whether the current distribution in the strip can be assumed uniform or not.

When a uniform current distribution is assumed throughout a thin strip line of width  $2L$ , the field  $H_x(x, y)$  at the distance,  $x$ , from the center of the strip line ( $z$ -axis) in the plane parallel to the strip line at a distance,  $y$ , from the strip line is given by

$$H_x(x, y) = \frac{I}{L} \left[ \pi - \tan^{-1} \frac{2yL}{L^2 - x^2 - y^2} \right], \text{ for } x^2 + y^2 \leq L^2$$

$$H_x(x, y) = \frac{I}{L} \tan^{-1} \frac{2yL}{x^2 + y^2 - L^2}, \text{ for } x^2 + y^2 \geq L^2$$

where  $L$ ,  $x$  and  $y$  are in mm,  $I$  is in amperes, and  $H$  is in oersteds.

If the ground plane is located at a distance  $d$  mm from the strip line, the field due to the ground plane is

$$H_{gx}(x, y) = \frac{I}{L} \tan^{-1} \frac{2(2d-y)L}{x^2 + (2d-y)^2 - L^2} \quad \text{for } x^2 + (2d-y)^2 \geq L^2$$

The total field is

$$H'_x(x, y) = \frac{I}{L} \left[ \pi - \tan^{-1} \frac{2yL}{L^2 - (x^2 + y^2)} + \tan^{-1} \frac{2(2d-y)L}{x^2 + (2d-y)^2 - L^2} \right]$$

assuming  $x^2 + y^2 \leq L^2 \leq x^2 + (2d-y)^2$

For  $x = y = 0$  and  $2d = L$ ,

$$H_x(0, 0) = 4.7 I/L$$

The above derivation assumes a constant current distribution. This assumption is valid for a sufficiently narrow strip line, but is not true for a wide line.

Without assuming a constant current density, H. J. Gray<sup>8</sup> has shown that the magnetic field  $H_x(x, y)$  in a shielded symmetrical strip-line can be expressed as:

$$H_x(x, y) = - \frac{I}{4K(k)} \operatorname{Re} \frac{\left( \pi/2d \right) \operatorname{sech} \frac{\pi}{2d} (x + jy)}{\sqrt{k^2 - \tanh^2 \frac{\pi}{2d} (x + jy)}}$$

where  $d$  is the distance between the strip-line and the ground plane (another ground plane is assumed to be above the strip-line at the same distance),  $K(k)$  is the complete elliptic integral of the first kind,  $k = \tanh \frac{\pi L}{2d}$ ,  $L$  is the half-width of the strip-line, and  $I$  is the total current.

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<sup>8</sup> H. J. Gray "Fields in Strip Lines for Film Memory Application" IEEE Trans. EC-13, 576-580. (1964).

The above expression may be used for the field near the strip-line (for  $x, y$  small compared with  $d$ ) in a non-symmetric strip-line with only one ground plane, though the actual field may be somewhat smaller, because it is not "compressed" by another ground plane.

Noting that  $H_x(x, 0)$  is equal to the current density,  $J(x, 0)$ , per unit width of the strip-line,

$$J(x, 0) = H_x(x, 0) = \frac{\pi I}{8dK(k)} \frac{1}{\sqrt{k^2 \cosh^2 \frac{\pi x}{2d} - \sinh^2 \frac{\pi x}{2d}}}$$

The fact that  $J(L, 0) = \infty$  means that the field as well as the current density is infinitely large at the edges,  $x = \pm L$ . This is quite different from the constant-current distribution.

The center field  $H_x(0, y)$  is

$$H_x(0, y) = \frac{\pi I}{8dK(k)} \frac{1}{\sqrt{k^2 \cosh^2 \frac{\pi y}{2d} + \sinh^2 \frac{\pi y}{2d}}}$$

It is noted that

$$H_x(0, 0) = \frac{\pi I}{8dK(k)} \approx \frac{I}{2\pi L}$$

Assuming  $L \ll d$ , hence  $k \approx \frac{\pi L}{2d}$  and  $K(k) = \frac{\pi}{2}$ , the edge field is:

$$H_x(L, y) \approx \frac{\pi I}{8K(k)} \frac{1}{\sqrt{2\pi ykd}} \quad \text{for } y \ll d$$

Note that the various assumptions give radically different answers. Furthermore, for the geometries of practical significance no feasible analytical approaches appear to exist, except perhaps computer solutions. However, as will be shown below, additional analytical difficulties arise, and together with these it appears that an experimental approach may be best for some time to come.

b. Demagnetizing Field. Contrary to parts of the literature, the demagnetizing field in a flat thin film is a vector concept, in the sense that it varies from place to place in the film. It is determined by the

difference of  $M$  at a point and the adjacent points, while  $M$  is determined in turn by the net field (applied fields plus the demagnetizing field) at those points. Thus the calculation of the demagnetizing field is very complicated.

When there is a magnetic charge  $q$  at  $(l, 0)$ , the  $x$  and  $y$  components of the demagnetizing field in c.g.s. units are

$$H_{xd} = - \frac{q}{r^2} \frac{l - x}{r}$$

$$H_{yd} = - \frac{q}{r^2} \frac{y}{r}$$

where  $r^2 = (l - x)^2 + y^2$ .

As a simple example, consider a single-domain film of size  $a \times b$ , and thickness,  $t$ , with the easy-axis along the  $a$ -edge. Let  $\theta$  be the angle between the direction of the saturation magnetization,  $M_s$ , and the easy-axis. The easy-axis component,  $H_{LD}$ , of the demagnetizing field at the center of the film is:

$$\begin{aligned} H_{LD} &= -2 \int_{-b/2}^{b/2} \frac{M_s t \frac{a}{2} \cos \theta}{\left[ \left( \frac{a}{2} \right)^2 + y^2 \right]^{3/2}} dy \\ &= - \frac{8M_s tb}{a \sqrt{a^2 + b^2}} \cos \theta = -A \cos \theta \end{aligned}$$

Similarly, the hard-axis component  $H_{TD}$  is:

$$H_{TD} = - \frac{8M_s ta}{b \sqrt{a^2 + b^2}} \sin \theta = -B \sin \theta$$

If these fields are added to the applied fields,  $H_L$ , and  $H_T$ , the energy expression becomes

$$E = \frac{1}{2} H_K M_s \sin^2 \theta - [H_L - A \cos \theta] M_s \cos \theta - [H_T - B \sin \theta] M_s \sin \theta$$

$$= \frac{1}{2} [H_K - 2A + 2B] M_s \sin^2 \theta - H_L M_s \cos \theta - H_T M_s \sin \theta + A M_s$$

Thus the effective value of  $H_K$ , which we shall denote by  $H_K^*$ , is

$$H_K^* = H_K - \frac{16 M_s t b}{a \sqrt{a^2 + b^2}} + \frac{16 M_s t a}{b \sqrt{a^2 + b^2}}$$

$$= H_K + \frac{16 M_s t (a^2 - b^2)}{ab \sqrt{a^2 + b^2}}$$

It is interesting to note that  $H_K$  is not affected when  $a = b$ .

It is also interesting to estimate the magnitude of the second term in  $H_K^*$ . Suppose

$$a = 1 \text{ mm} = 10^{-1} \text{ cm (40 mils)}$$

$$b = 0.25 \text{ mm} = 2.5 \times 10^{-2} \text{ cm (10 mils)}$$

$$t = 500 \text{ \AA} = 5 \times 10^{-6} \text{ cm}$$

$$M_s = 10^4 \text{ gauss} = 8 \times 10^2 \text{ c.g.s.u.}$$

then

$$\frac{16 M_s t (a^2 - b^2)}{ab \sqrt{a^2 + b^2}} = 2.56 \text{ oe}$$

If  $H_K$  is  $3.0 \text{ oe}$ , then the correction term is of comparable magnitude. This would indicate that the demagnetizing field is certainly too large to be neglected.

The foregoing discussion assumed that there were net magnetic charges  $\pm M_s \cos \theta$  or  $\pm M_s \sin \theta$  at the edges. Actually this is very unlikely from the energy point of view, because the demagnetizing field would then be infinitely large at the edges. It would be more realistic to assume that there is no magnetic charge at the edges. In this sense, the concept of a single domain is self-contradictory, because the single domain cannot exist without having free magnetic charges at the edges.

As an example of how the demagnetizing field is calculated from a known distribution of magnetization, consider a strip of film of thickness  $t$ , which is infinitely long in the  $y$  direction. When there is a net line charge  $\Delta M(u_1)$  along  $x = u_1$ , and  $\Delta M(-u_2)$  along  $x = -u_2$ , the demagnetizing field  $\Delta H_D(x)$  in the  $x$  direction is:

$$\begin{aligned}\Delta H_D(x) &= \int_{-\infty}^{\infty} \frac{\Delta M(u_1) t (u_1 - x)}{[(u_1 - x)^2 + y^2]^{3/2}} dy - \int_{-\infty}^{\infty} \frac{\Delta M(-u_2) t (u_2 + x)}{[(u_2 + x)^2 + y^2]^{3/2}} dy \\ &= \frac{\Delta M(u_1) t}{u_1 - x} - \frac{\Delta M(-u_2) t}{u_2 + x}\end{aligned}$$

When  $\Delta M(u)$  is known as a function of  $u$ , the total demagnetizing

field is calculated as 
$$H_D(x) = \int_{-L}^L \Delta H(x) du$$

Let us assume a form of  $M(u)$  satisfying the following conditions:

- (1)  $M(u) = M(-u)$  and  $\Delta M(-u) = -\Delta M(u)$
- (2)  $\Delta M(\pm L) = 0$  (no charge at the edges)
- (3)  $M(0) = M_s$
- (4)  $\Delta M(0) = 0$  (no charge at the center)

One such form of  $M(u)$  is

$$\begin{aligned}M(u) &= M_s (L^3 - 3L^2 u^2 + 2u^3) / L^3 \quad \text{for } 0 \leq u \leq L \\ &= M_s (L^3 - 3L^2 u^2 - 2u^3) / L^3 \quad \text{for } -L \leq u \leq 0\end{aligned}$$

and 
$$\begin{aligned}\Delta M(u) &= 6 M_s u(u - L) \Delta u / L^3 \quad \text{for } 0 \leq u \leq L \\ &= -6 M_s u(u + L) \Delta u / L^3 \quad \text{for } -L \leq u \leq 0\end{aligned}$$

$$\begin{aligned} \text{Then, } H_D(x) &= \frac{6M_s d}{L^3} \left[ \int_0^L \frac{u(u-L)}{u-x} du + \int_{-L}^0 \frac{u(u+L)}{u+x} du \right] \\ &= - \frac{6M_s d}{L^3} \left[ 1 + \frac{x(L-x)}{L^2} \log \left| \frac{L-x}{x} \right| - \frac{x(L+x)}{L^2} \log \left| \frac{L+x}{x} \right| \right] \end{aligned}$$

It is noted that  $H_D(x) = H_D(-x)$

$$H_D(0) = -6 M_s d / L^3$$

$$H_D(\pm \frac{1}{2} L) = 0.18 H_D(0)$$

$$H_D(\pm L) = (1-2 \log 2) H_D(0) = -0.38 H_D(0)$$

The demagnetizing field becomes zero at  $x$  slightly larger than  $L/2$  and changes sign for greater values of  $x$ . This can be interpreted from Fig. 6. The fact that the demagnetizing field can be in the same direction as the magnetization has also been pointed out by H. J. Kump.<sup>9</sup>

A more elaborate one-dimensional analysis using a computer has been reported by H. J. Kump.<sup>9</sup> He used the single-domain model equations to determine  $\Delta M$  from the total field (demagnetizing field plus applied field by a narrow strip line). The boundary condition is that the total net field at the edges is zero, that is, the demagnetizing field is equal to the applied field in magnitude but is opposite in sign at the edges. The results show that it is difficult to orient the entire (or nearly entire) film at  $90^\circ$  from the easy axis because of the non-uniformity of the applied field and the large demagnetizing field. Here the easy axis is assumed to be in the direction of the strip.

To see the effect of the demagnetizing field on switching, it is necessary to consider two orthogonal fields and the analysis must be done on a two-dimensional basis. It is convenient to assume that the film consists of a number of tiny rectangular single-domains, with

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<sup>9</sup> H. J. Kump, "Demagnetization of Flat Uniaxial Films Under Hard Direction Drive," IBM Journal 9, 118 (1965).

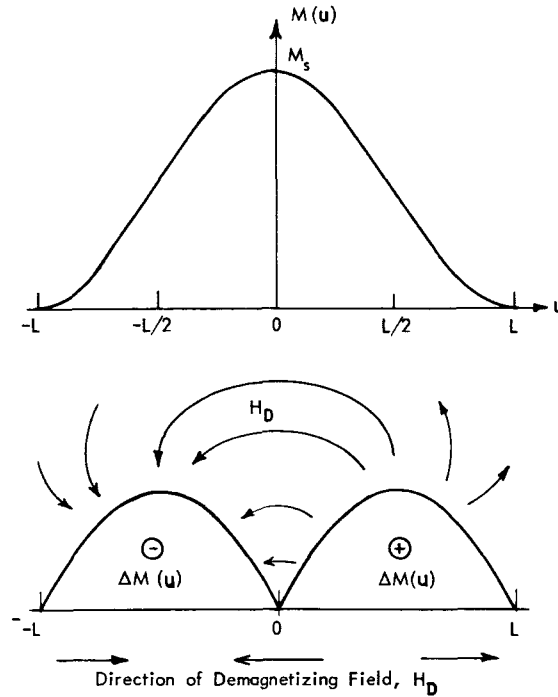


Fig. 6. Demagnetizing field.

the easy axis in the  $x$  direction. The demagnetizing field  $H_D(x, y)$  at any point  $(x, y)$  can then be calculated by counting the contribution from each and every domain.

It would be interesting to solve this problem with the aid of a computer and to see how much area of the film switches at a certain level of applied fields and to determine the shape of that area. Actually, however, this is a two-dimensional problem and its solution would require a very long computer time. Moreover, the assumption that the single domain theory is applicable to each individual cell might not be realistic especially where switching is involved. For these reasons, the computer solution has not been attempted.

c. Eddy Current. The eddy current is induced in a metal by a changing magnetic field. The total eddy current in a metal sheet of thickness,  $t$ , width,  $a$ , length,  $\ell$ , as shown in Fig. 7, can be shown to be<sup>10</sup>

$$i = \frac{t^2}{8} \frac{\ell}{\rho} \frac{dB}{dt} \quad \text{for } a \gg d$$

where  $\rho$  is the specific resistivity.

<sup>10</sup> R. F. Soohoo, "Magnetic Thin Films", Harper and Row (1965), p. 137.



There are two kinds of magnetic fields present in a drive conductor. One is the field produced by the other drive line and the other is the piercing flux from the film. The eddy current due to the former

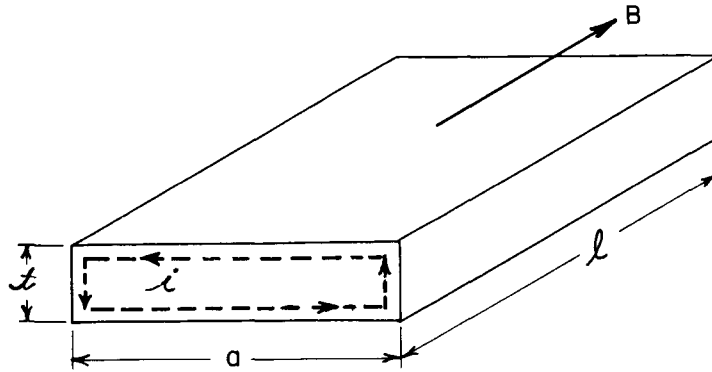


Fig. 7. Eddy current flow in a metal sheet.

acts to shield the magnetic field and thus distort it. The eddy current due to the latter acts as a damping torque against flux change. Thus, it tends to return the switched magnetization to its previous state and hence slows down switching. The effective  $H_k$  is increased by this damping effect. When a metal substrate is used, the eddy current induced in the substrate must also be taken into account, because it also opposes any change in magnetization.<sup>11</sup> There is also speculation that the magnetic thin film has a metallic behavior in supporting eddy currents over its surface and, therefore, severely distorting the field configuration.

A detailed analysis of the eddy current effect is very complicated and it is difficult to get even an approximate expression. T. A. Smay<sup>12</sup> has attempted an approximate analysis but the assumptions used are too crude to be justifiable.

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<sup>11</sup> J. G. Edwards, Proc. IEEE, 112, 1081-90 (1965).

<sup>12</sup> T. A. Smay, "Energy Transfer Properties of Thin Magnetic Film Logical Elements," Ph.D. Thesis, Iowa State University, 1962.

As for actually observed effects of eddy currents, there are conflicting reports. It is J. S. Eggenberger's<sup>13</sup> conclusion that the rotation mode of switching is difficult to achieve in a strip line configuration of reasonable size (1 mm width or so). According to J. G. Edwards,<sup>11</sup> eddy current effects are not significant in 0.5 mm(20 mil) - wide strip lines, though the effects are appreciable in lines more than 1 mm (40 mils) wide.

#### 5. Preparation of Thin Magnetic Films

As part of the program of investigating a coincident-frequency memory, the vacuum evaporation of films has been undertaken in our laboratory.

The evaporation of films of nickel-iron alloy near the zero magnetostrictive composition of 81 percent Ni, 19 percent Fe, by weight, has been made from an electrically heated tungsten helical filament. The source material used is 10-mil alloy wire of composition 83 percent Ni, 17 percent Fe. The choice of a starting material of lower iron composition is due both to the tendency of the tungsten filament to form an alloy with the nickel and to the higher vapor pressure of iron.<sup>14</sup> The film is deposited in the presence of a 45-oersted uniform field onto a heated, 40-mil thick, glass substrate, placed 19" above the source. The field induces the direction of the uniaxial anisotropy axis (easy-axis). A substrate temperature of 350°C is maintained by a quartz radiation heater for one hour before evaporation; it is lowered to room temperature during a minimum of two hours following evaporation, throughout which time the 45-ø field is applied. The slow rate of cooling prevents fracture of the film through stress. It has been found that a filament temperature of 1600°C, measured by an optical pyrometer, produces an evaporation rate of 50 Å per second. The evaporation pressure is 10<sup>-5</sup> mm, Hg.

Continuous sheet films of thickness 200 Å, 600 Å and 1000 Å have been evaporated. Their coercive properties as obtained from hysteresis-loop tracer measurements at 1000 cps are:

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<sup>13</sup> J. S. Eggenberger, J. App. Phys. 5, 287S (1960).

<sup>14</sup> D. O. Smith, J. App. Phys. 30, 264 S(1959).

$$\begin{array}{ll}
 H_c = 2.0 \text{ oe} \\
 H_k = 3.5 \text{ oe}
 \end{array} \left. \vphantom{\begin{array}{l} H_c \\ H_k \end{array}} \right\} \begin{array}{l} \text{for a series of 200 \AA films} \\ \text{evaporated at 300}^\circ\text{C substrate} \\ \text{temperature} \end{array}$$
  

$$\begin{array}{ll}
 H_c = 2.0 \text{ oe} \\
 H_k = 3.0 \text{ oe}
 \end{array} \left. \vphantom{\begin{array}{l} H_c \\ H_k \end{array}} \right\} \begin{array}{l} \text{for a series of 600 \AA films} \\ \text{evaporated at 300}^\circ\text{C substrate} \\ \text{temperature} \end{array}$$
  

$$\begin{array}{ll}
 H_c = 3.6 \text{ oe} \\
 H_k = 2.6 \text{ oe}
 \end{array} \left. \vphantom{\begin{array}{l} H_c \\ H_k \end{array}} \right\} \begin{array}{l} \text{for a 1000 \AA film evaporated} \\ \text{at 350}^\circ\text{C substrate temperature} \end{array}$$

By going to the higher substrate temperature of 350°C, it was found that the median dispersion angle was reduced from 3° to less than 1°, as measured by the Crowther dispersion technique.<sup>15</sup> Skew has also been reduced to within 1° by adjustment of the 45 oe orienting field direction.

A series of 200 Å films has also been evaporated through a mask having 40-mil wide slots. The average coercive-field parameters for these films are:

$$\begin{array}{ll}
 H_c &= 1.5 \text{ oe} \\
 H_k &= 2.5 \text{ oe}
 \end{array}$$

Since the surface nature of the substrate critically affects the magnetic properties of the film formed upon it,<sup>16</sup> the reasonably low values obtained for  $H_c$ ,  $H_k$ , indicate that both the substrate material (MICRO-LUSTRA, fire-polished, drawn glass) and cleaning technique are satisfactory. It is believed that the degree of surface cleanliness has also resulted in the extremely good adhesion for all films evaporated.

Further research in the control of evaporation parameters will be necessary in order to verify that increasing the substrate temperature to 350°C reduces the dispersion as well as  $H_k$ , and to verify that mask-evaporated strip films have lower  $H_c$ ,  $H_k$  values than continuous sheet films evaporated under the same conditions. (Etching into strips produced higher  $H_c$ ,  $H_k$  values.)

<sup>15</sup> T. S. Crowther, Lincoln Laboratory Group Report No. 51-2 (1959), revised 30 March 1960.

<sup>16</sup> A. C. Moore, A. S. Young, J. App. Phys. 31, 279S (1960)

When a standard evaporation procedure has been established for single layer Ni-Fe films, the evaporation of multi-layer films of Ni-Fe | M | Ni-Fe, in which M is either a non-magnetic metal<sup>17</sup> or a dielectric<sup>18</sup> film will be made. Our laboratory vacuum system is adequately suited to multiple source evaporation. It is believed that multilayer films have thresholds for creep and noncoherent rotation which are much nearer the idealized case, and so are more suitable for a coincidence type of memory.

6. Domain Observations Using the Bitter Technique

As previously explained, it has been found that after a write operation has been performed on a film, the read-out is non-destructive. Except for films where some spontaneous reversal of the magnetization takes place and the field cancelling that of the earth is not removed, the magnetization does not change with time. Valuable information would, therefore, be obtained by examining the domain structure resulting from various combinations of longitudinal and transverse write fields. Since the Bitter technique yields more detailed information of the domain wall structure than does the Kerr magneto-optic effect, a preliminary investigation of several of the films tested in the memory has been made using the Bitter technique.

It has been found that the use of modified bright field reflected illumination, with objective lens immersion in the colloid, shows detailed edge domain structures at a magnification of 2000 x. These edge domains have been observed with the film outside the memory and appear to nucleate around small ( $\approx 3$  micron) indentations in the edges of etched strip films. Mask evaporated films, on the other hand, do not appear to have a similar edge domain structure. It is, therefore, planned to investigate the domain structures resulting from the application of write field pulses. Since it is important that cancellation of

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<sup>17</sup> E. Feldkeller et al., "Improved Magnetic Film Elements for Memory Application", INTERMAG Conf. Proc. p 8-4-1; (1965).

<sup>18</sup> J. C. Bruyere, et al., C. R. Acad. Sc. Paris 258, 841 et 1423 (1964).

the earth's field takes place during writing and the subsequent domain observations, the observations will be made with the film remaining in position in the memory. It is hoped that correlation will be found between the improved write properties of multilayer films, the calculated effects of the various factors influencing switching, and the visual observations of domain configurations.

## PUBLICATIONS OF THE PROJECT

### CURRENT PUBLICATIONS

#### REPORTS

Conduction Processes in Thin Films, Status Report  
ESL-SR-245, June, 1965.

Aponick, A. A., "A Study of CdS Thin-Film Vacuum-  
Analog Triodes", Memorandum ESL-TM-247,  
December, 1965.

#### THESES

Cooper, M. S., "Variation of Differential Capacitance  
of Cadmium Sulfide Thin-Film Diodes", Master of  
Science Thesis, Department of Electrical Engineering,  
Massachusetts Institute of Technology, August, 1965.

### PAST PUBLICATIONS

#### REPORTS

Aponick, A. A., Jr., "An Investigation of Thin-Film  
Gold Structures on CdS", Report ESL-R-237, May,  
1965. (Also published as a Master of Science thesis,  
May, 1965.)

Conduction Processes in Thin Films, Status Report  
ESL-SR-225, December, 1964.

#### THESES

Gajda, W. J., Jr. "Hole Conduction in Thin Films  
of CdS", Master of Science thesis, Department of  
Electrical Engineering, Massachusetts Institute of  
Technology, June, 1965.

Jenssen, H. P., "De-excitation of CdS Films by High  
Electric Fields", Bachelor of Science thesis, De-  
partment of Electrical Engineering, Massachusetts  
Institute of Technology, June, 1965.

Oliver, M. R., "Negative Resistance in Cadmium  
Sulfide Thin Film Diodes" Bachelor of Science thesis,  
Department of Electrical Engineering, Massachusetts  
Institute of Technology, June, 1965.